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Notes on Lunar Ilmenite

M. Hutson

Lunar and Planetary Laboratory

The University of Arizona

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Opaques (mostly ilmenite) make up 0-5% of highland rocks, 1-11% of low-Ti mare basalts, and 10-34% of high-Ti mare basalts (Carter 1988). Apollos 11 and 17 sampled high-Ti basalts. Apollos 12 and 14 sampled low-Ti basalts. Apollo 15 sampled a complex mixture of mare and highland material. Apollo 16 sampled mainly highland material (Taylor 1975).

Mare Basalts (Rocks)

Ilmenite is the third most abundant mineral in Apollos 11 and 17 rocks. It is very conspicuous in Apollo 11 samples, with platy crystals occasionally reaching several millimeters in size (Levinson and Taylor 1971, Mason and Melson 1970). Ilmenite is found in a wide variety of shapes, ranging from euhedral to anhedral, blocky, tabular, platy, and skeletal forms (Fron del 1975, Levinson 1971). Ilmenite also occurs as rims surrounding armalcolite cores. These rimming ilmenites generally contain exsolved rutile and spinel (Fron del 1975). However, most ilmenite is homogeneous, and the ilmenites associated with armalcolite and exsolved rutile are "relatively rare and quantitatively minor" (Levinson and Taylor 1971).

Lunar ilmenite is almost pure  $\text{FeTiO}_3$ ; a Mossbauer study of Apollo 11 ilmenite found no detectable ferric iron (Mason and Melson 1970). The following minor and trace elements have also been reported: Apollo 11— $\text{Al}_2\text{O}_3$ , 0.1-0.3%;  $\text{MnO}$ , 0.3-0.6%;  $\text{CaO}$ , up to 0.3%;  $\text{Cr}_2\text{O}_3$ , 0.1-1.3%;  $\text{V}_2\text{O}_3$ , up to 0.2%;  $\text{Zr}_2\text{O}_3$ , up to 0.3%; and  $\text{MgO}$ , up to 6.0% (Mason and Melson 1970). Ilmenite appears to be the major host phase for Zr (Levinson and Taylor 1971). There does not appear to be any relationship between  $\text{MgO}$  content of ilmenite and its grain size or mineral association (Fron del 1975), although some researchers have suggested that high-magnesian ilmenite is associated with armalcolite (Fron del 1975). Levinson and Taylor (1971) state that high-magnesian ilmenite in Apollo 11 samples occurs as small tabular grains totally enclosed in pyroxene. Apollo 14 ilmenite contains 0.2-0.6 wt%  $\text{ZrO}_2$  and up to 3.9 wt%  $\text{MgO}$ , which is noteworthy as the whole rock has lower  $\text{MgO}$  than that from other Apollo sites (approximately 8-8.5 wt%). In addition, ilmenite from one Apollo 14 sample contained  $\text{Ti}^{+3}$  (El Goresy et al. 1972). Apollo 17 sampled two types of basalts with different crystallization histories. Ilmenite is found as primary blocky crystals in both types of basalt and as rims around armalcolite in Type II basalts (El Goresy et al. 1974). Apollo

17 ilmenite contains 0.55–0.70 wt% MnO, 1.51–4.68 wt% MgO, and 0.48–1.05 wt% Cr<sub>2</sub>O<sub>3</sub> (El Goresy et al. 1974).

### Mare Soils

The lunar regolith contains material ranging from fines to blocks meters across. The material with grain size less than 1 mm is referred to as soil (Taylor 1975). This soil consists of mineral grains, rock fragments, glasses, and agglutinates, which are "glassy, rock and mineral fragments welded together by glass" (Taylor 1975). Agglutinates constitute up to half of the material in some size fractions (Levinson and Taylor 1971; Agosto 1988). As a result, the amount of ilmenite which is easily separated from lunar soils is considerably less than the normative ilmenite. This was shown by McKay and Williams (1979), who report modal abundances of 2.2% and 4.9% for Apollo 11 and 17 soils with normative abundances (calculated from TiO<sub>2</sub> contents) of 14.7% and 15.5%, respectively. They note that the available ilmenite in the average Apollo 17 mare soil is only one-third of the normative ilmenite. McKay and Williams (1979) also suggest that ilmenite abundance increases with decreasing grain size fraction. However, a study of Luna 24 soils does not support this correlation (Laul et al. 1987).

Fron del (1975) reports the results of x-ray studies; lunar and terrestrial ilmenite appear to have identical crystal structure parameters. She concludes: "It would appear that until we have many more x-ray and chemical analyses of both lunar and terrestrial ilmenites, the lunar ilmenite and its earthly counterpart can be assumed to be the same." However, it is known that reduction of lunar ilmenite is more difficult than for terrestrial ilmenite, due to the lack of ferric iron in the lunar ilmenite (Briggs 1988).

Finally, McKay and Williams (1979) note that hydrogen is implanted in lunar soils by the solar wind. Data on hydrogen content of lunar soils are sparse and not in good agreement. Reported bulk soil hydrogen contents range from 30–145 ppm. McKay and Williams (1979) note that ilmenite is known to retain helium much more readily than other minerals. Although there are no data for hydrogen, they speculate that if hydrogen is retained similarly to helium, it could exist at the 1000 ppm level in lunar ilmenite.

### Beneficiation

A discussion of possible techniques for mining and beneficiation of lunar ores is given by Williams et al. (1979). However, it appears that only William N. Agosto has actually attempted to separate ilmenite from lunar soils in the laboratory (Agosto 1984, 1985, 1988). Agosto has done electrostatic separation experiments on simulant soils

(made with terrestrial ilmenites) and a 90-150 micron size fraction of an Apollo 11 soil. The experiments were run both in a vacuum and in a nitrogen atmosphere. Only 30% of the ilmenite was recovered in one pass in the vacuum (it is not clear whether he is referring to lunar or simulant ilmenites), while much better results were obtained using a nitrogen atmosphere, because of the density difference between ilmenite and other minerals in the soil (Agosto 1988). Ilmenite in the lunar simulant was concentrated from 10 wt% to 95 wt%, with 68% of the ilmenite recovered after one pass in nitrogen. Ilmenite in the Apollo 11 soil was concentrated from 10 vol% to 54 vol%, with 45% recovery after one pass (Agosto 1984). Perhaps some combination of magnetic and electrostatic separation is needed.

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